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Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology
National Institute of Standards and Technology
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FLAME LENGTH AND FLAME HEAT TRANSFER CORRELATIONS IN CEILING FIRES

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ABSTRACT

Flame length and flame heat transfer correlations are obtained for circular flames developing radially beneath an unconfined inert ceiling, and are compared against the correlations for one-dimensional flames in a downward channel. The both correlations resulted in the proportionality of the area covered by a ceiling flame to heat release rate and the sole dependence of flame heat transfer on the distance from the source normalized by the flame length. Heat release rate per unit flame area is found to be smaller with circular flames than with one-dimensional flames, which seems to mean a weaker entrainment of ambient air in circular flames than in one-dimensional flames. The weak heat flux from a ceiling flame suggests the importance of the preheating of combustible ceiling by hot gas layer for the fast fire spread generally observed in real and experimental room fires. Flame spread tests with Midium Density Fiberboard ceiling showed very weak flame spread and support this conclusion.

Keywords: *ceiling fire, flame length, heat flux, heat release rate.*

INTRODUCTION

Flame development beneath a ceiling is very often the direct trigger for the occurrence of flashover. In spite of the importance of ceiling fires for fire safety, there are few laboratory measurements on this phenomenon. In a previous study by the authors[1], experimental correlations for flame length and flame heat transfer were reported on a downward channel simulating one-dimensional ceiling fires as a first step for the quantitative understanding of ceiling fires. That study revealed a proportionality of the length of a ceiling flame to heat release rate and single dependence of the flame heat flux on the relative distance from the injection normalized by flame length. The proportionality of the flame length to heat release rate suggested a uniform entrainment of air to the flame all over the flame, and is consistent with the assumptions for so-called "linearized flame approximation". Indeed, analysis on flame spread tests using Midium Density Fiberboard(MDF) showed a good agreement between the test results and the flame spread behavior predicted using the linearized flame approximation. Another important result of the previous study is that the heat flux from a one-dimensional ceiling fire is considerably weaker than in wall fires and flame spread beneath a one-dimensional MDF ceiling is much weaker than that along a vertical surface of the same material as long as the combustible surface is not exposed to any external heat source.

This observation was however hardly consistent with experience with real fires and large scale burn tests which have generally demonstrated development of ceiling fires more dramatic than wall fires. This discrepancy was attributed to the preheating of the whole ceiling surface by a smoke layer in a large scale room fire. However, since ceiling fires in real buildings is more complicated than one-dimensional fires, it was felt necessary to run experiments on other ceiling configurations for leading further understanding of the significance of ceiling fires. In this study, measurements of flame size and flame heat transfer have been made on radially flowing steady flames beneath an inert ceiling. The results are compared with those on one dimensional ceiling fires to quantify the controlling mechanism of ceiling fires. Flame spread tests are also carried out using MDF.

EXPERIMENTAL ARRANGEMENT AND MEASUREMENTS- Circular Ceiling Fires

Figure 1 shows the experimental arrangement. The 1.82m x 1.82m unconfined noncombustible ceiling was composed of two layers of 12mm thick fiber-reinforced cement boards(Perlite).

During the flame radius and flame heat transfer measurements, 90mm and 160mm diameter porous round burners were installed downward flush to the ceiling surface. Propane was used as the fuel. Measurements were made on the heat flux to the ceiling, fuel supply rate and the radius of the flames. Heat flux was monitored with Schmidt-Boelter heat flux gages with their surfaces flush to the ceiling. Flame geometry was recorded with digital video cameras; reported flame radius will be the time average of the location of flame tips from the center of the burner measured with eyes for at least 3 minutes with the interval of one second on video tape. Fuel supply rate to the burner was in the range of 3.3 l/min to 33 l/min. The whole apparatus was located beneath a hood connected to an exhaust duct and a fan. Gas analysis was made in the exhaust duct to measure effective heat release rate by the oxygen consumption method. The measured effective heat release rate was generally considerably lower than the heat release rate assuming the complete combustion. This suggests a lower combustion efficiency in a ceiling fire than in a wall fire.

Observation of the flame spread beneath a combustible ceiling was made with a 12mm thick MDF applied to the surface of the inert ceiling and the 0.16m diameter burner as the fire source with its injection surface rearranged flush to the combustible surface. No external heating source was used for the flame spread tests. Surface temperature of the Midium Density Fiberboard was monitored with 0.1mm Chromel-Alumel thermocouples.

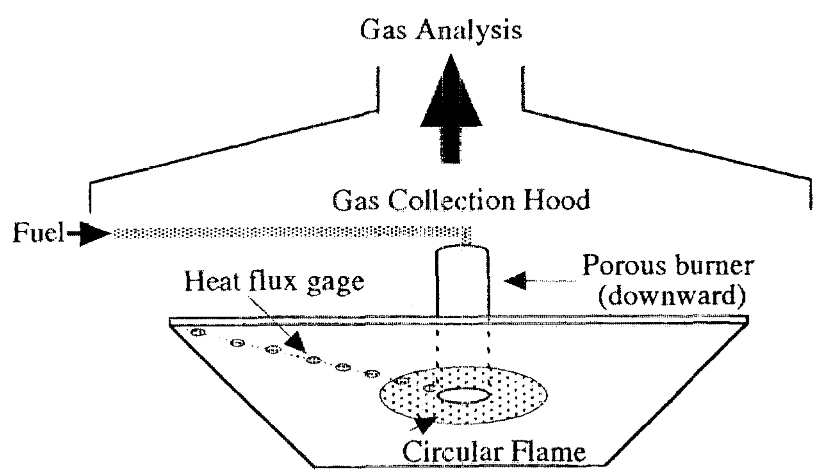

Figure 1 Experimental Arrangement, Circular Ceiling Flames

EXPERIMENTAL RESULTS

Flame Radius and Flame Area

Figure 2 summarizes the correlation between the radius of the area covered by the visible flame and heat release rate measured by Oxygen Consumption Method. Solid and intermittent flames were much less distinguishable than in one-dimensional ceiling fires and wall fires. According to Figure 2, flame radius is nearly proportional to the square root of the heat release rate. While the flame radius is slightly smaller for the 0.16m diameter burner than for the 0.09m diameter burner, the difference seems to diminish with increase of heat release rate. With a circular ceiling flame enough larger than the injection source, it is believed that the flame radius become independent of the source size. The power dependence of the flame radius suggests a proportionality of the flame area to heat release rate, which has already been reported for one-dimensional ceiling fires.

Figure 3 is a summary of the relation between the area covered by the flame and heat release rate for the present experiments and the one-dimensional flames obtained from the previous experiment. Flame area is nearly proportional to the heat release rate whether for one-dimensional ceiling fires or for circular ceiling fires, but flame area for a circular ceiling flame is close to three times that for a one-dimensional ceiling flame of a given heat release rate. This suggests a notably weaker entrainment of ambient air into the flame per unit area in radially flame spread than in one-dimensional flame spread.

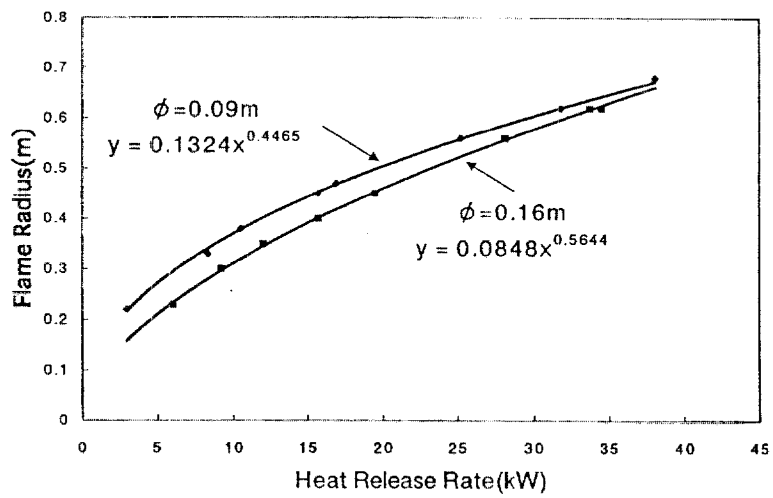

Figure 2
Flame radius and heat release rate

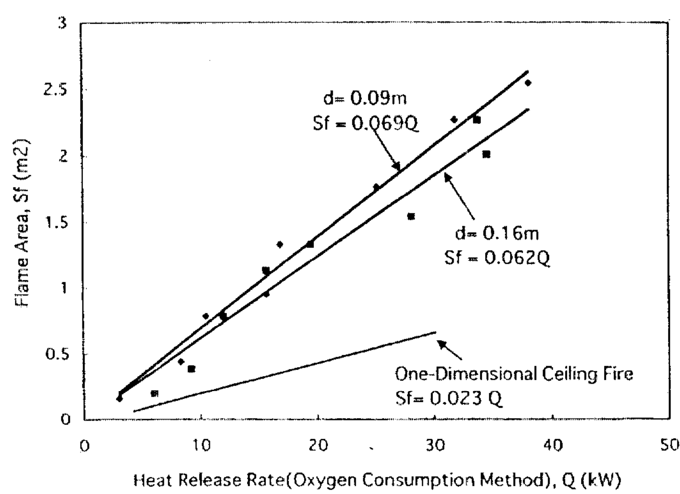

Figure 3
Flame area and heat release rate

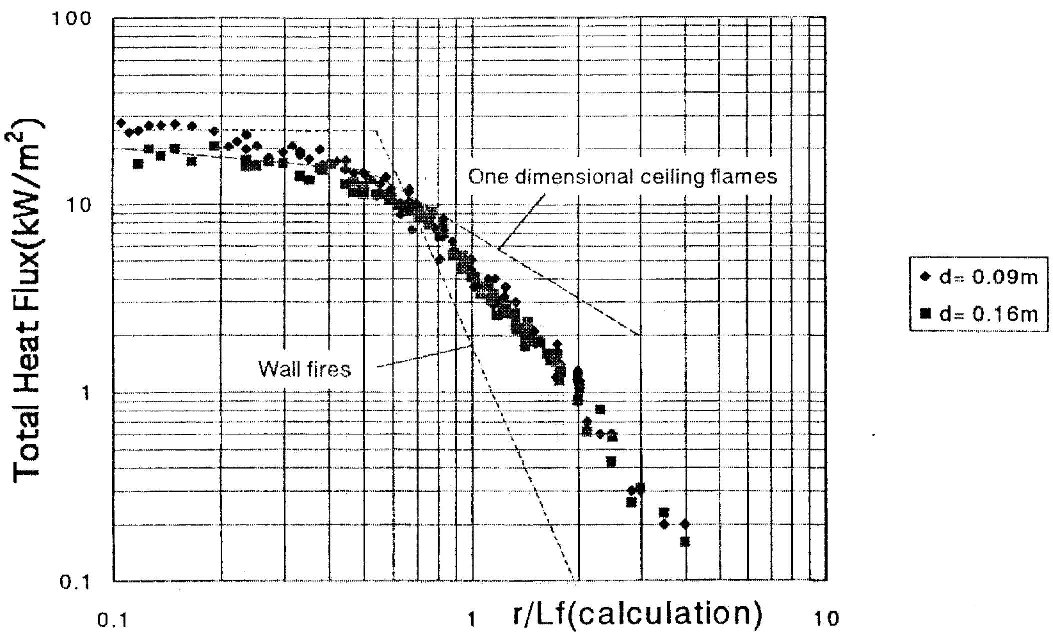

Figure 4 Flame heat flux vs. radius normalized by calculated flame radius

Flame Heat Transfer

Results of the flame heat transfer measurements are summarized against the distance between heat flux gage and the center of the injection source, r, normalized by the flame radius, Lf, in Figure 4. The flame radius used for this correlation was calculated from heat release rate using the regressive formula in Figure 2. Figure 4 also shows the flame heat flux distribution for wall fires and one-dimensional ceiling flames. The results of the present tests are found to be highly concentrated along one single curve, whilst heat flux near the injection source is slightly larger with the 0.09m diameter source than with the 0.16m diameter source. The heat flux is nearly uniform for r/Lf below 0.40 and then starts to decay gradually with increasing distance. The plateau heat flux, within the range of 20 - 30kW/m², is close to that for one-dimensional ceiling fires and is weaker than that for wall fires. The slope representing the decay is notably steeper than for the one-dimensional ceiling fires, and is less steeper than for wall fires. The steeper decay of flame heat flux for radial ceiling fires than for one-dimensinal ones is probably because of the faster decay of convective heat transfer due to the faster decrease of velocity in radial convection than in one-dimensional convection.

The comparison between the two modes of turbulent flames beneath a ceiling seems to suggest weaker contribution of flame heat transfer to concurrent flame spread in radial flame spread than in one-dimensional ones. Also, it is believed that the high plateau heat flux is delivered generally only to the pyrolyzing surface, and the unburnt surface beyond the pyrolysis front is exposed to only weak heat flux, which may not be enough to ignite wood based materials in a reasonable period for "smooth" spread of a flame. This suggests that the accelerated flame spread along a combustible ceiling commonly observed in room fires is caused by the uniform heating by the hot gas layer rather than the progressive heating by the ceiling flame. Provided that the temperature rise in the hot gas layer reaches 200K, gross total heat flux from the hot gas layer should reach several kW/m², which is already comparative or even larger than the heat flux beyond the flame front of a ceiling fire.

Flame Spread beneath a MDF Ceiling

Figures 5, 6 and 7 are a summary of the time-history of the location of the flame front and estimated pyrolysis front, and heat release rate for different intensity of the fire source. Fire source intensity is excluded from the reported heat release rate. The location of the pyrolysis front was estimated by the surface temperature arriving the ignition temperature of MDF, 380 ℃. Although flame front reached relatively long, surface burning did not develop beyond the extent of the flame from the fire source. The ultimate burn pattern was roughly consistent with the maximum estimated pyrolysis front. The extremely weak flame spread without external heating seems to endorse the weak heating of unburnt surface by a ceiling flame. This result also support the insignificant role of the flame heat transfer for the development of fires beneath a combustible ceiling.

CONCLUDING REMARKS

Measurements of flame heat transfer and flame spread beneath a ceiling have been conducted using an unconfined inert and combustible ceilings. Following conclusions can be drawn on flames and flame spread beneath a combustible ceiling.

(1) Area covered by a ceiling flame is nearly proportional to heat release rate.

(2) Area covered by a ceiling flame per unit heat release rate depends on the mode of flame spread, and is larger with circular flames than with one-dimensional flames.

(3) Flame heat flux distribution is represented as a function of the location relative to the flame length for each mode of ceiling fires. Heat flux is nearly constant for r/Lf less than around 0.4 and is within the range of 20～30kW/m^2 . Flame heat flux beyond the flame front is weaker for circular ceiling flames than for one-dimensional fires.

(4) Flame heat transfer in a ceiling fire does not seem to be enough to maintain and accelerate flame spread. The significant spread of ceiling flames generally seen in real and experimental room fires is attributed to the uniform heating of combustible ceiling by the hot gas layer.

TERMINOLOGY

d: burner diameter
Lf: flame length, flame radius
Q: heat release rate
Qo: heat source intensity
Sf: horizontal area covered by a ceiling flame
r: radius

REFERENCE

[1]Hasemi,Y., Yoshida,M., Yokobayashi,Y., and Wakamatsu,Takao: Flame Heat Transfer and Concurrent Flame Spread in a Ceiling Fire, Proceedings of the Fifth International Symposium on Fire Safety Science, Melbourne, 1997.

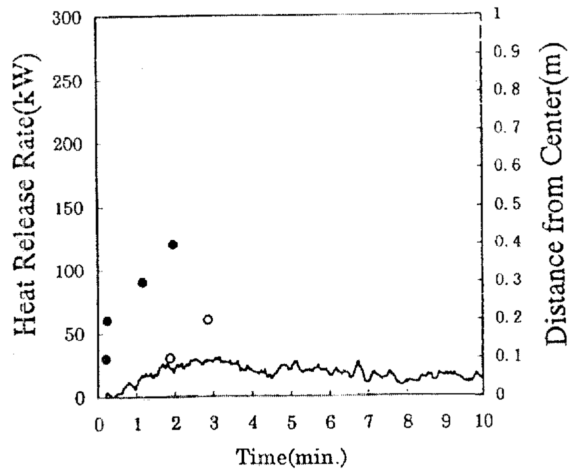

Figure 5 Flame spread on MDF
Qo= 9.7kW
solid line: heat release rate
○: estimated pyrolysis front(380℃)
●: location of flame tips

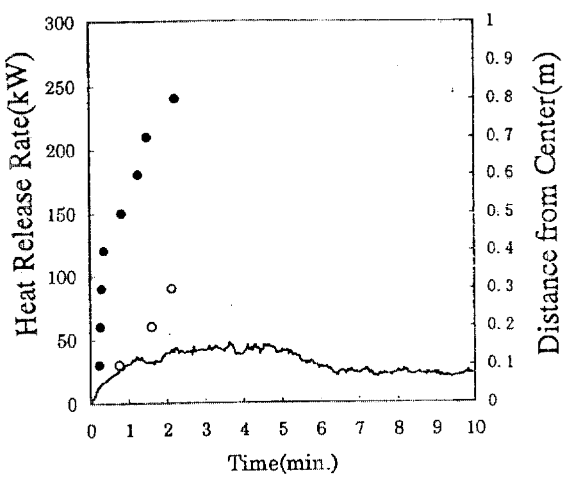

Figure 6 Flame spread on MDF
Qo= 16.2kW
solid line: heat release rate
○: estimated pyrolysis front(380℃)
●: location of flame tips

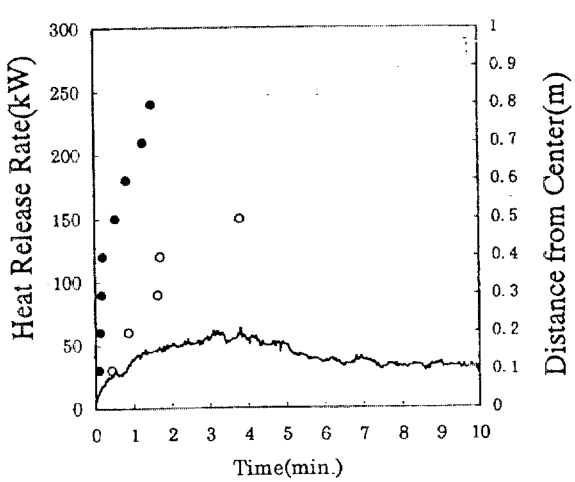

Figure 7 Flame spread on MDF
Qo= 22.6kW
solid line: heat release rate
○: estimated pyrolysis front(380℃)
●: location of flame tips